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GENESIS AND EVOLUTION OF GYPSUM TUMULI

JOSÉ M. CALAFORRA* AND ANTONIO PULIDO-BOSCH
Department of Hydrogeology and Analytical Chemistry, University of Almeria E-04120 Almeria, Spain

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ABSTRACT

Tumuli are hollow subcircular domes of the most superficial stratum of gypsum, principally found in outcrops of macrocrystalline gypsum. They vary from a few centimetres to several metres in diameter and reach maximum heights of a little more than 1 m. The relationships between the morphostatistical parameters that define these formations are: $h = r/3$ and $e = r/9$, where h is the elevation of the raised layer, e its thickness and r the mean radius. Their genesis has caused some controversy over the involvement of phenomena such as hydration of anhydrite, or tectonic processes capable of explaining this folding. This paper shows their genesis linked to the dissolution of macrocrystalline gypsum and reprecipitation of microcrystalline gypsum within the same gypsiferous layer. It has been calculated that to reach the theoretical saturation within the few centimetres' thickness of the cap of the tumulus, water infiltration velocities are required of between $0{\cdot}002\ \mathrm{cm\ s^{-1}}$ for an uplifted stratum of 2 cm thickness, and $0{\cdot}03\ \mathrm{cm\ s^{-1}}$ for 30 cm thickness. These velocities imply the existence of very slow rates of infiltration and/or capillary movement of water within the gypsiferous layer. The secondary microcrystalline gypsum is precipitated in the intercrystalline and intracrystalline voids of the gypsum crystals, producing an increase in porosity and associated volume that causes the doming of the gypsiferous layer. The development of tumuli is a cyclic process which is favoured by a sequence of short wet and dry intervals which, in turn, facilitate the almost simultaneous processes of dissolution and precipitation. These conditions predominate in arid and semiarid climates where intense evaporation can occur suddenly following sporadic infiltration. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: gypsum mounds; doming; anhydrite; dissolution; precipitation; gypsum karst

INTRODUCTION

Tumuli are one of the most singular surface features, as yet scarcely described, that are found in gypsum within the karstic landscape. They consist of domes of the surface layer of the gypsum that are semispherical in form and may reach several metres in diameter (Figure 1). Tumuli were described for the first time in the gypsiferous karst of Sorbas, Spain (Pulido-Bosch, 1982, 1986; Calaforra, 1985) and subsequently in Bologna (Forti, 1987) and Sicily (Macaluso and Sauro, 1996). However, it is likely that they also occur in other outcrops of gypsiferous karst, especially under semiarid conditions, and some examples have recently been cited from the gypsum karst of New Mexico (Calaforra, 1998).

In this paper the word tumulus (plural: tumuli) is used to refer to these structures. This was the term first used to describe them and their morphology reflects the true etymological sense of the word which derives from the Latin and refers to small burial mounds fashioned from earth, consisting of domes in the form of small hillocks. Thus the term gives a clear idea of their morphology.

The principal objective of this paper is to demonstrate that, at least in the case of tumuli developed on macrocrystalline gypsum, the processes of dissolution and reprecipitation within the same gypsiferous layer can produce the observed folding. Furthermore, we wish to deduce the role played by structural controls and the influence of the texture of the gypsum in their formation. Tumuli must be considered as superficial karstic mesoforms (Calaforra, 1996; Calaforra and Pulido-Bosch, 1996, 1997), characteristic of certain gypsiferous karstic landscapes, given that their origin can be related to subsurface processes of dissolution and precipitation.

* Correspondence to: Dr J. M. Calaforra, Department of Hydrogeology and Analytical Chemistry, University of Almeria, E-04120 Almeria, Spain. Email: jcalafor@ualm.es
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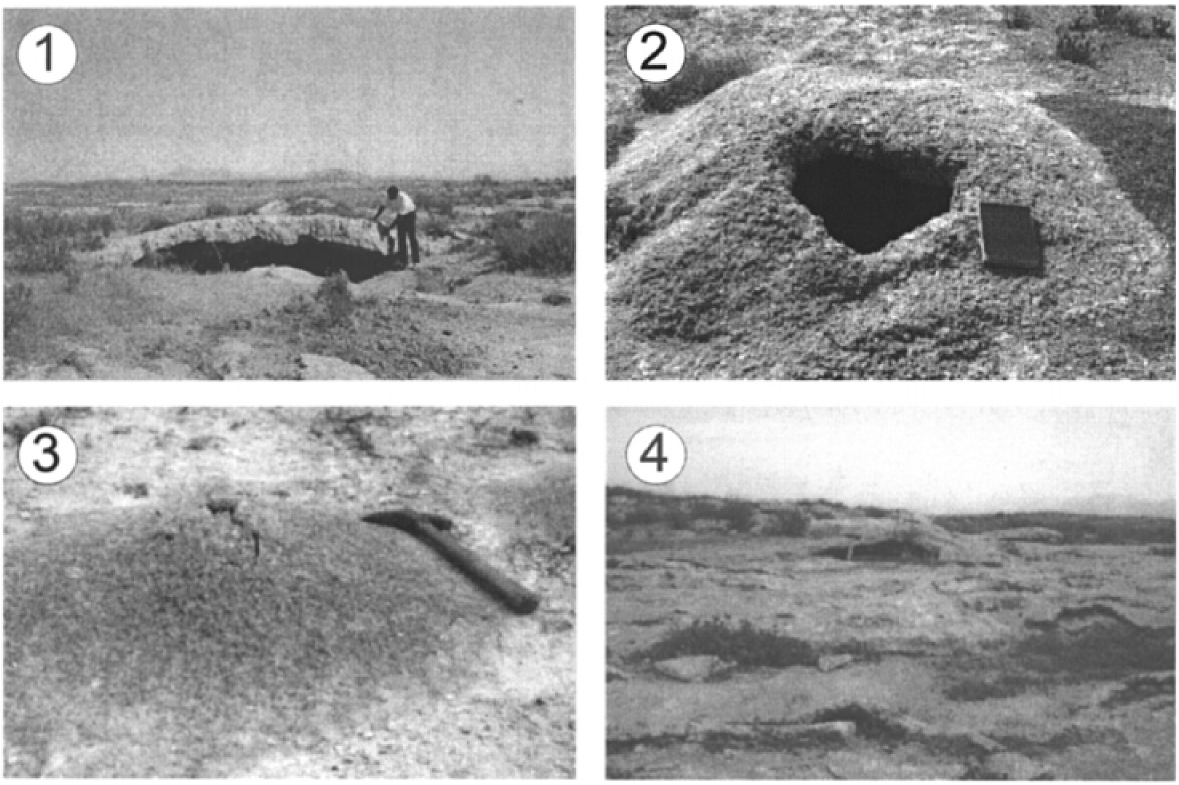

Figure 1. Tumuli: subcircular landforms caused by doming of an outcropping gypsum stratum (Sorbas Karst, Spain). (1) One of the biggest tumuli; (2) cap breakdown tumulus; (3) cupola tumulus; (4) karren field of tumuli

Three different hypotheses were considered to explain the formation of tumuli. These embrace all the factors that might influence their possible formation: tectonic factors, mineralogical transformations and processes of dissolution and precipitation (Calaforra, 1985). They are summarized below.

1. *Tectonic hypothesis*. Tumuli could be the response to compressive tectonic forces which occurred in the area in very recent or contemporary geological times. The elliptical or circular morphology would simply be the result of the ellipsoid of strength causing local deformation.
2. *Increase in volume*. This is based essentially on the mineralogical change from anhydrite to gypsum. The increase in volume associated with this transformation (about 27 per cent of the volume) would be the principal agent of tumulus formation. The hydration front would progress from the surface to depth, such that the folded strata would be located in the most superficial layer.
3. *Dissolution and precipitation processes*. The porosity of the gypsiferous matrix, relatively rich in macrocrystalline gypsum, allows dissolution and recrystallization phenomena. Infiltration water from precipitation, low in salts, dissolves the gypsum by means of small fissures and hollows in the macrocrystalline gypsum matrix. Subsequently, high evaporation rates lead to saturation of these fluids and the recrystallization of gypsum in inter- and intracrystalline spaces. The deposition of this solid material causes tensions which provoke an increase in volume, which in turn creates gentle doming of the stratum.

Each of these hypotheses will be discussed after describing the methods of analysis and their results. In particular, reference will be made to the historically accepted increase-in-volume hypothesis, against the hypothesis of dissolution–reprecipitation presented in the current article.

METHODOLOGY

With the aim of obtaining a set of descriptive statistics of this curious surface feature, a series of measurements was made of the morphological characteristics of the tumuli present in the gypsum karst of Sorbas, one of the best examples of gypsum karst where these forms are widely distributed. The parameters measured were: the radius or long and short semiaxes of the semiellipsoid (*a* and *b*); the thickness of the dome (*e*); and the elevation of the outer surface of the dome with respect to its base (*h*). In addition, an estimate was made of the coefficient of circularity, defined as $(a - b)/a$, as well as of the linear relationships between the various parameters measured.

Samples were collected at different depths within the caps of tumuli to determine mineralogy and texture using X-ray diffraction and scanning electron microscopy (SEM) techniques. Special attention was focused on an analysis of microcrystalline gypsum arising from reprecipitation within the gypsiferous macrocrystalline matrix.

In additional to the geomorphological analysis of these features, a theoretical study was undertaken to demonstrate that it is feasible to reach saturation of the gypsum over a short time period and within the limited volume provided by the few centimetres of raised cap layer of the tumulus. For this, reference is made to the laboratory experiments of Kemper *et al.* (1975), and the equations of Keisling *et al.* (1978) are applied to the particular case of the tumuli. Keisling *et al.* (1978) showed that the coefficient of gypsum dissolution, K (cm^{-1}), can be expressed according to the following equation:

$$K = \nu / \left[\left(\frac{\nu^2 + 4D\alpha}{4D^2} \right)^{1/2} - \frac{\nu}{2D} \right]$$

where ν ($cm\ s^{-1}$) is the mean water velocity across the layer, D the coefficient of dispersion ($cm^2\ s^{-1}$) and α the coefficient of mass transfer (cm^{-1}). Keisling *et al.* (1978) proposed the use of the mean value of D ($150\ cm^2\ s^{-1}$) for all cases and the following empirical relationship to calculate α, deduced from experimental data gathered by Kemper *et al.* (1975):

$$\alpha = 0{\cdot}0043\, s^{1{\cdot}48}$$

where s is the area of the gypsum grains per unit volume. This equation covers grain sizes from 2 to 40 mm. In the case of the cap layer of the tumuli the grain size of the crystals of the raised stratum ranges between these values and so the proposed approximation for the estimation of the coefficient of mass transfer is valid for the case of infiltration through the domed layer of a tumulus.

When the values of K are plotted against Darcy's flow (q), or equivalently, against the mean velocity ν for the same porosity in the layer, it is observed that the coefficient of dissolution is quite uniform for grain sizes of about 40 mm. For the current analysis an α value of $0{\cdot}0035\ cm^{-1}$ was taken as the mean value of K for the macrocrystalline texture of the tumuli.

On the basis these premises one can use an equation of mass transfer as a function of time which relates the concentration of $CaSO_4$ in the flow within the gypsum cap to the coefficient of dissolution. This has the form:

$$\ln\left(\frac{C_s - C_b}{C_s - C_0} \right) = K t_b$$

where C_b is the concentration of $CaSO_4$ in the water crossing the cap layer, C_0 is the initial concentration (rainwater or overnight condensation), C_s is the concentration at saturation point, K is the coefficient of gypsum dissolution described above, and t_b is the mean flow time across the cap. This equation enables the calculation, from a theoretical point of view, of the mean velocity of water crossing the tumulus, using the relationship $t_b = L/V$, where L is equivalent to the mean thickness of the uplifted layer (e).

RESULTS

Morphostatistical description of the gypsum tumuli

A total of 81 structures were measured in the Sorbas gypsum karst, of which 33 were approximately circular in form and 48 elliptical; 47 had a perforated cupola due to gravitational instability originating during uplift.

The diameter of the tumuli measured in the Sorbas gypsum karst ranged between 20 cm and almost 12 m, giving an idea of the variability in scale that these forms can present. The mean value of the long (a) and short (b) axes was 1·8 m and 1·3 m respectively.

A calculation of the coefficient of circularity gives a mean value of 0·15, such that 46·3 per cent of the tumuli measured had a circularity between 0·0 (circular form) and 0·1, and only 10 per cent exceeded a value of 0·4. The great majority can be considered as subcircular forms as far as their cross-section is concerned.

Other parameters measured were the thickness of the raised gypsum layer (average 10 cm and maximum 0·5 m) and the maximum height of the cupola (average 33 cm and maximum 1·35 m).

There is no doubt that the parameters measured are related to one another due, amongst other reasons, to strictly mechanical considerations. Linear regression was used to define statistically an approximate relationship between the various parameters measured. Table I summarizes the results obtained, and Figure 2 shows the scatter plots with each of the lines of best fit plotted. It can be readily deduced that the elevation of the tumuli has a close relationship with the diameter or axis length ($R = 0{\cdot}90$ and 0·94) and with the thickness of the raised cap, and that this, in turn, is related to the length of the two axes ($R = 0{\cdot}95$ and 0·93).

Reducing the equations to a simple linear expression, it is possible to see that the maximum height that a tumulus can reach (h) is approximately three times the thickness of the layer undergoing the doming process (e):

$$h \cong \frac{1}{3}r; e \cong \frac{1}{9}r$$

$$h \cong 3e$$

Table I. Statistical size parameters of the tumuli: r = radius when circular; a and b = ellipse semi-axes; $(a - b)/a$ = circularity coefficient; h = height; e = thickness. Equations for linear regression: n = number of samples; R = correlation coefficient

	Parameter	Mean (m)	Standard deviation
Circular forms	r	1·56	1·17
Elliptical forms	a	1·78	1·96
	b	1·32	1·42
Circularity	$(a - b)/a$	0·15	0·16
Height	h	0·33	0·28
Thickness	e	0·10	0·10

	Correlation with	n	Equation	R
	a	36	$h = 0{\cdot}29\ a + 0{\cdot}96$	0·90
Height (h)	b	36	$h = 0{\cdot}35\ b + 0{\cdot}06$	0·94
	e	36	$h = 2{\cdot}20\ e + 0{\cdot}09$	0·90
Thickness (e)	a	46	$e = 0{\cdot}09\ a + 0{\cdot}01$	0·93
	b	46	$e = 0{\cdot}12\ b + 0{\cdot}00$	0·95

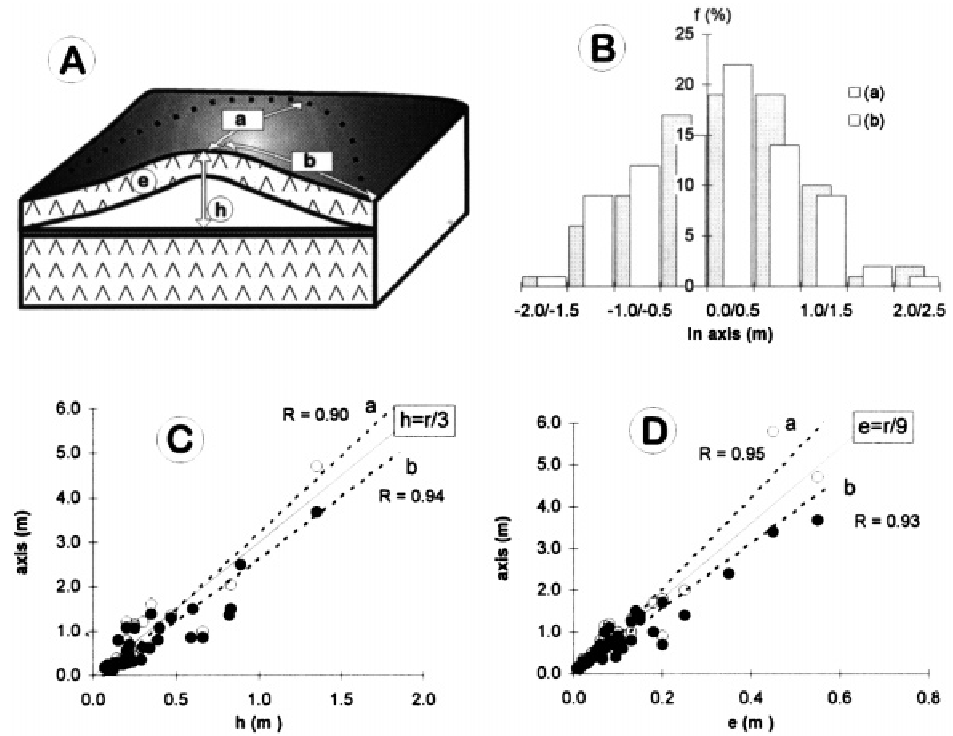

Figure 2. Relationship between different morphological parameters of tumuli. (A) Long semiaxis (*a*), short semiaxis (*b*), thickness of the uplifted layer (*e*), maximum height of the dome (*h*). (B) Frequency distribution of the semiaxis lengths (*a* and *b*). (C) Linear regression plot of the height versus semiaxis length (dashed lines). (D) Linear regression plot of the thickness versus semiaxis length (dashed lines), correlation coefficients (*R*) and mean simplified equations for subcircular forms (solid lines)

Measurements taken in Italy (Forti, 1987) also accord with the data obtained in the Sorbas karst. The only difference is that the Italian data show a greater scatter (the correlation coefficients calculated for the same relationships between parameters are all less than 0·90). This may be due to various factors that might indicate the ideal conditions for tumulus development.

(a) The lower number of well developed tumuli observed in the gypsum karst area of Bologna does not enable the homogenization of data that can be obtained for the Sorbas karst.
(b) The greater tectonic fracturing which exists in the Bologna Gypsum Vein does not favour the development of these landforms and, when they are present, their geometry is often controlled by earlier tectonic structures (small superficial fractures). The presence of intense fracturing, more or less perpendicular to the stratification, does not appear to favour the devlopment of tumuli. Where the ground is fractured it is common to encounter pressure ridges (Macaluso and Sauro, 1996) instead of the uniform folding of the gypsum layer to form a tumulus.
(c) The substantial thickness of the soil cover present above the gypsum outcrop in Bologna does not appear to facilitate the development of forms such as tumuli. In the Sorbas karst there are large areas of bare gypsum outcrop with no soil cover, a property of the landscape which is difficult to find in the Bolognese situation. The direct exposure of gypsum favours tumulus formation.
(d) The climatology of the zone may be one of the most important factors in the development of landforms such as these. The intense evaporation occurring in the Sorbas area and the semiarid conditions would appear to favour the formation of tumuli.

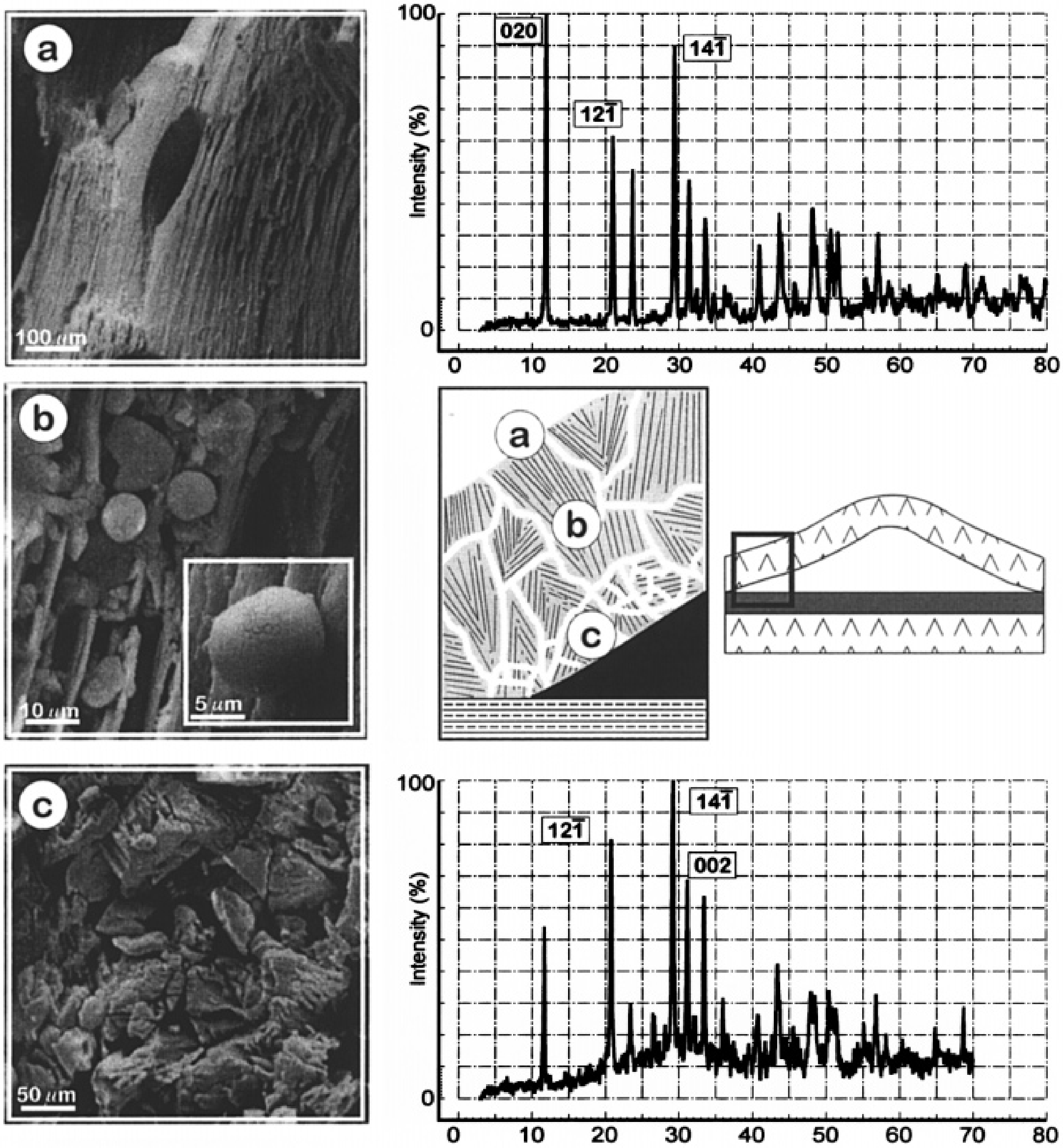

Figure 3. SEM microphotographs and X-ray diffraction analysis of a tumulus. (a) Micropits on the (010) faces on the surface of the tumulus. (b) Exfoliation planes with dissolution and reprecipitation of gypsum microcrystals. Inset: endolithic algae found in the centre of the tumulus layer. (c) Mass of gypsum microcrystals in the lower part of the tumulus layer. X-ray analysis of the macrocrystals (a) and microcrystals (c) showing the composition of the tumulus layer ($CaSO_42H_2O$), differences in the maximum intensity for the faces of the crystals and the degree of crystallinity.

Mineralogical analysis of the tumuli

In order to determine the influence of gypsum texture and mineralogy on the genesis of tumuli, data derived from SEM microphotographs were employed, taken at different levels within the domed layer of the tumuli (Figure 3).

In the first phase, dissolution of gypsum is detected within the first few centimetres, where direct percolation acts. The presence of nanopits and micropits (Figure 3a) can be seen on the exposed surfaces of the gypsum crystals. These frequently exhibit microkarren in a ‘zig-zag’ formation (Forti, 1996) and etch pits developed by the ‘layer-by-layer’ process (Bosbach and Rammensee, 1994) on the (010) face, probably

related to screw dislocations (Bosbach *et al.*, 1995). Another type of dissolution is preferentially produced as a result of the numerous weak points present within the gypsiferous crystals, such as the planes of crystalline exfoliation. This situation also sees the development of nanorillen when the exposed faces are not pinacoid or are not generally parallel to the principal exfoliation (010). The surface (010) of gypsum crystals is hydrophilic (Finot *et al.*, 1997) which proves that dissolution of an intracrystalline character can be produced due to the exfoliation planes. Subsequent precipitation of microcrystals between these same planes of exfoliation would expand the crystal, progressively separating the planes of exfoliation.

In Figure 3b one can see that the dissolution has been accentuated and that it has been clearly selective, in that the exfoliation planes of the gypsum crystal are the preferred planes of percolation and dissolution. In this way, a marked secondary porosity is set up due to the intra- and intercrystalline dissolution. Saturation is quickly achieved, so long as the flow is very slow. Certain organic activity can also be seen in this microphotograph with the presence of endolithic algae (see inset microphotograph), whose possible action on the microkarstification of karst has been described for other semiarid climes (Smith *et al.*, 1996). These algae, together with cyanobacteria (Oren *et al.*, 1995) usually form a fairly continuous green layer at a depth of about 2 cm below the surface, favoured by the light penetration through the gypsum crystals, a feature which can also be observed in the uplifted strata of the tumuli.

In the second phase, intense evaporation, characteristic of semiarid regions, produces the immediate precipitation of these saturated fluids in the existing voids between the crystals. The recrystallized gypsum generated by this means is microcrystalline (Figure 3c), in contrast to the original gypsum which has a marked selenitic texture. This microcrystalline gypsum displays an intergranular porosity far greater than the macrocrystalline type (i.e. a qualitative increase in volume: voids as well as microcrystals). The volumetric compensation has to be translated into folding (tumuli) or fracturing (pressure ridges) of the layer undergoing the process and this, together with the very force of crystallization of this neoformed gypsum, might possibly be the cause of separation and lifting of the gypsiferous layer. It is important to note that this process would not be instantaneous, but progressive: the tumulus would continue to grow until the stability of the vault thus formed was compromised, leading to its own collapse.

In addition to providing an understanding of the composition of the gypsiferous layer, the X-ray diffraction diagrams in Figure 3 indicate a structural differentiation between the original macrocrystalline gypsum (Figure 3a) and the microcrystalline gypsum of neoformation (Figure 3c). There are differences between the two in respect of the relative intensity that each one of their crystal faces registers, being greater for the pinacoidal faces of the original macrocrystals. The baseline of diffraction intensity is greater for the microcrystalline reprecipitated gypsum than for the microcrystalline type, and this reflects the lesser degree of crystallinity.

Gypsum solution and precipitation in a gypsum tumulus

As an additional problem, it remains to be shown whether it is possible to achieve saturation within the gypsum over the few centimetres depth afforded by the elevated cap layer using the mass transport equation. Curve (1) in Figure 4 shows the variation in the concentration of $CaSO_4$ as a function of the time taken to cross the gypsiferous layer of the tumulus. The theoretical time to achieve saturation in gypsum is relatively short. Thus saturation can rapidly be obtained in the gypsiferous layer, so long as the water remains in contact with the gypsum crystals throughout the time indicated for infiltration. It can be seen that to obtain a concentration close to saturation (2150 mg l^{-1} of $CaSO_4$), somewhat more than 1030 s (about 18 min) contact time is required between the water and the tumulus layer. As well as the downward movement of the infiltration water, the upward capillary movement associated with evaporation processes must also be considered, which can contribute to a greater water–rock contact and can accelerate the process of supersaturation. In fact, especially in semiarid climates, the processes of evaporation significantly limit the leaching depth and cause gypsum deposition from supersaturated soil solutions under high evaporation rates close to the surface (Amit and Yaalon, 1996).

Further, curves (2) and (3) in Figure 4 enable an appreciation of the relationship between the concentration of $CaSO_4$, obtained after crossing the tumulus cap layer, and the mean velocity at which the flow must circulate to acquire this concentration. The plot shows two extreme cases: tumuli with domes of 2 cm and

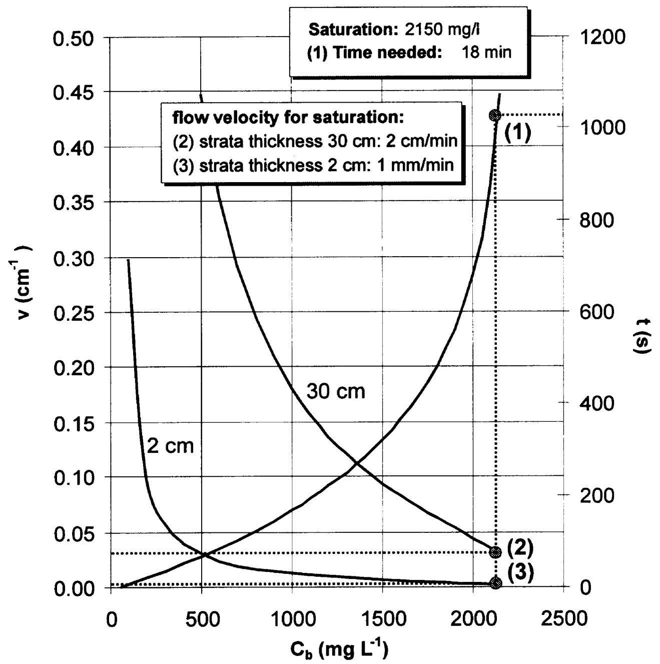

Figure 4. Theoretical interpretation of infiltration time and transit velocity for water crossing a tumulus to reach the gypsum saturation. About 18 min is needed to reach a concentration of 2150 mg l^{-1}. When the stratum has a thickness of 2 cm the necessary velocity is 1 mm min^{-1} (0·002 cm s^{-1}), and in the case of tumuli of 30 cm thickness the velocity can increase to 2 cm min^{-1} (0·03 cm s^{-1}) to reach saturation in gypsum

30 cm thickness. One can deduce that the mean velocity required to achieve a concentration close to saturation point within the tumulus ranges from approximately 0·002 cm s^{-1} in the case of small tumuli with uplifted stratum of 2 cm thickness to 0·03 cm s^{-1} for large tumuli with an uplifted stratum of 30 cm thickness.

Between these two types of tumuli it has been possible to observe significant textural differences which accord with the results obtained. The smaller tumuli exhibit, in general terms, a porosity and permeability significantly less than the large ones. Permeability is a dynamic parameter, variable over time, and this concept is also applicable in the case of the tumuli: as a tumulus is being formed, the dissolution processes markedly affect the permeability and effective porosity of the gypsiferous layer. The values of both parameters increase progressively to the point of compromising the equilibrium between the cohesivity produced by the recementation of the domed layer and its own dissolution. In short, the progressive increase in permeability is translated into mechanical instability of the raised layer of the tumulus and can eventually lead to its collapse, especially in the case of the large tumuli.

From this starting point, a laboratory analysis was performed of the infiltration rate of a sample of the collapsed roof of a tumulus of 30 cm thickness. This yielded a very high mean value of 0·15 cm s^{-1}, which gives some idea of the great quantity of interconnected voids (intercrystalline spaces, separated exfoliation planes existing in the gypsiferous layer). The value obtained is excessively high if it is compared with the mean transit velocity calculated to reach saturation in a layer 30 cm thick (0·03 cm s^{-1}). This fact suggests that the limit of stability of the tumulus might already have been exceeded, and an inability to achieve gypsum saturation at such high mean infiltration rates results in the process of dissolution becoming dominant over the reprecipitation of gypsum, such that the tumulus ceases to expand and begins to break down.

In any case, a slow capillary flow of infiltration water seems to be a requirement for the recrystallization *in situ* in the gypsiferous cap layer, given that through the use of laminar and turbulent flow Raines and Dewers (1997) demonstrated that reactive solutions can penetrate much further into gypsum-bearing karst than previously thought possible because the surface control of gypsum dissolution rates, which becomes more significant at higher fluid flow velocity, has the effect that the dissolution rates decrease as saturation in gypsum is approached.

DISCUSSION

This section presents an analysis of the formation hypotheses presented at the start of the paper, together with evidence for the existence of quasi-simultaneous dissolution and precipitation in the gypsum outcrops as the cause of the uplifting of the tumulus.

The tectonic hypothesis is effectively invalidated. Measurements of the direction of the long axes of each of the elliptical tumuli reveal a wide scatter of values, and this practically eliminates the possibility that the tumuli are formed in response to a general compressive tectonic strength over the outcrop. For one thing, the folding affects only a single gypsum stratum. An additional argument against this hypothesis is provided by certain configurations in tumulus fields where it is observed that the same stratum has lifted and fallen on various occasions. One would have to argue for an excessive number of compressive phases for a phenomenon which, given its characteristics, can only develop in the surface layer of the gypsum and must certainly be recent or contemporary.

The increase in volume attributed to the conversion of anhydrite to gypsum is a hypothesis expounded in the past to explain the genesis of very similar features in Triassic gypsiferous materials in Germany, called 'Quellungshölen' which, in some cases, can constitute true cavities or 'quellungs caves' (Kempe, 1996). Breish and Wefer (1981) describe these forms, naming them 'gypsum bubbles', and proposing their formation by compressive forces that separate the gypsum layer from the underlying anhydrite with a hydration front approximately horizontal to the surface. The argument for the creation of these landforms, based on an increase in volume due to hydration of the anhydrite, also put forward by Reimann (1991), is, in our judgement, applicable to the specific case of the German Triassic with its large areas of anhydrite, outcropping to a greater or lesser extent. However, it is not valid for the Messinian gypsum where anhydrite is absent.

In spite of the morphological similarity between the quellungs and the tumuli, and the fact that they are frequently cited as the same landform (Ford and Williams, 1989), there exist certain consistent differences that enable a completely different hypothesis to explain their formation.

In the case of quellungs, these are occasionally found with several strata folded together due to a lowering of the hydration front, which generally occurs at several metres' depth (Pechorkin, 1985). In this case, the curvature of folding diminishes with depth as the hydration front is attenuated. In the case of the macrocrystalline Messinian gypsum without anhydrite, only the most superficial stratum is folded, with no detection of the existence of a hydration front. There again, in the tumuli the unfolded strata situated immediately below the domed cap are usually a discontinuity or a narrow stratum of intercalated clays, whilst in the case of the quellungs it may be formed by the same layer of anhydrite, not hydrated. However, there are certainly similarities between the tumuli and the quellungs in addition to their morphology, since both are attributed with a very recent or contemporary origin. In fact, Reinboth (1997) notes the growth of a quellung of 3 m diameter and 30 cm elevation in little more than 30 years.

In any case, a dissimilarity that we consider key in differentiating the origin of quellungs and tumuli is based on the texture of the gypsiferous rock that undergoes the folding. In quellungs, this comprises microcrystalline gypsum as opposed to macrocrystalline gypsum in the tumuli. The high intergranular and intragranular porosity of the domes of the tumuli makes one think that the processes of intralayer dissolution and reprecipitation may play an important role in the doming of the stratum.

One morphostatistical difference between the two forms that should be cited is that quellungs achieve greater heights of up to nearly 3 m (Reimann, 1991), whilst the maximum elevation recorded for tumuli is 1·35 m (Pulido-Bosch, 1986). In this way the relationship between the elevation reached and the length of the axes (h/L) can approach values of 0·27 in quellungs (Reinboth, 1997) whilst for tumuli the value is significantly less (0·16).

In summary, the increase-in-volume hypothesis, whereby an increase in volume is produced by the conversion of anhydrite to gypsum, presents serious difficulties in attempting to explain the formation of the tumuli described in the Messinian gypsum of Sorbas. The first and most important problem is that neither anhydrite nor pseudomorphic gypsum have been detected in the samples taken from the Sorbas gypsiferous series. The mineralogical analyses undertaken show anhydrite to be absent (see X-ray diffraction diagrams in

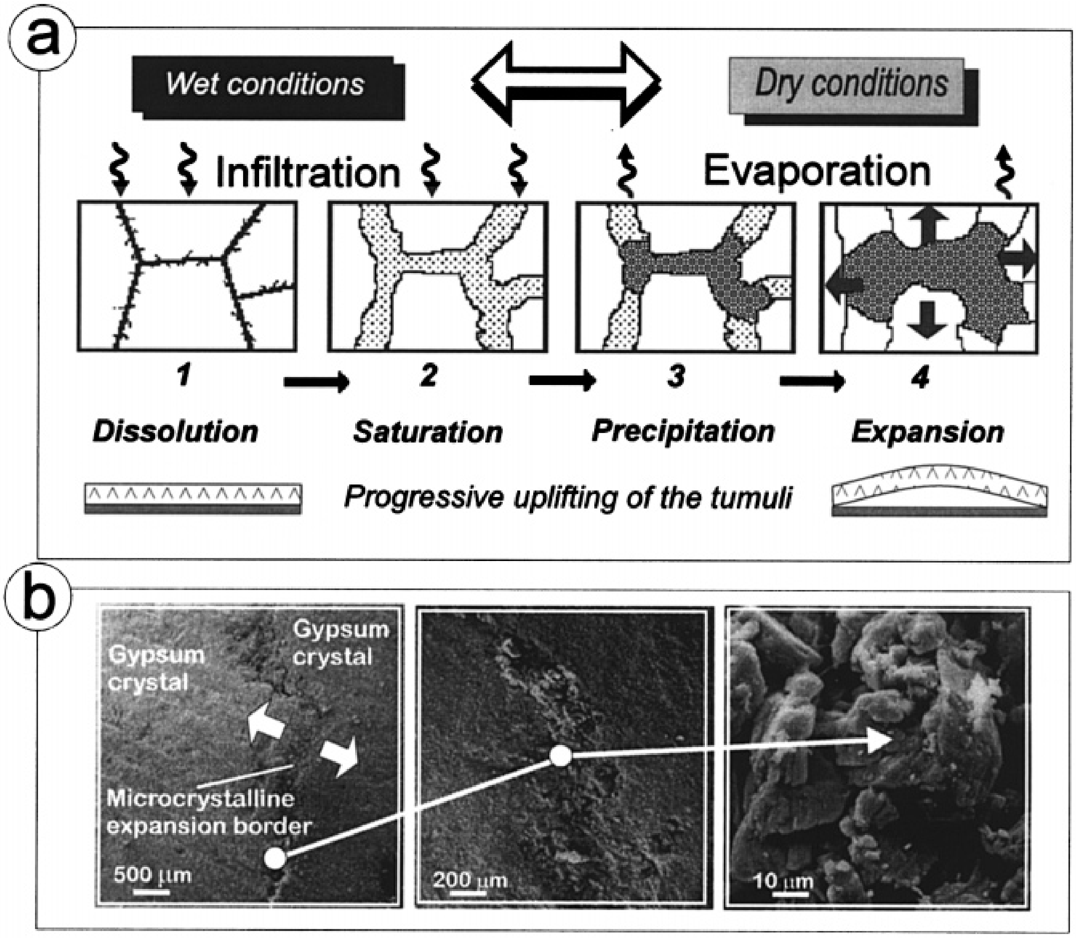

Figure 5. Hypothetical cycles in the formation of tumuli. (a) For the formation of tumuli extreme climatic conditions (wet–dry cycles) are preferable, with a short period cycle, just as occurs in arid and semiarid climates. In this way, after expansion (4) due to gypsum precipitation (3), corrosion of the interstices (1 and 2) can begin again, and thus the domed gypsum layer becomes more convex until its eventual breakdown. (b) Successive enlargement of SEM microphotographs showing the microcrystalline reprecipitation of gypsum in the interstices between the macrocrystals of a tumulus

Figure 3) between the macrocrystals of the Messinian gypsum and thus underline the difficulty of using the hypothesis of volume change by hydration to explain the genesis of the tumuli.

The third hypothesis described above and relating to the processes of precipitation and dissolution is possibly the most straightforward in concept since it requires neither distinct, recent tectonic phases nor mineralogical changes to explain the development of tumuli. This hypothesis is the one we have adopted as the explanation of the genesis of tumuli, by virtue of the rejection of the two earlier hypotheses and because of the presence of certain geomorphological and microtextural proofs which support its expression.

In support of this hypothesis, certain characteristics of the tumuli exist which can be considered as geomorphological proof of its validity. On occasions, one can observe the process of uplifting of the gypsiferous layer repeated over and over again on the same tumulus, generally one of small size, giving rise to concentric circles of pressure ridges. This fact imposes the requirement that the process be continuous, with lifting and collapse of the small tumuli on repeated occasions. This requirement is made possible by postulating a cyclical process of dissolution and precipitation.

From the point of view of the statistical analysis undertaken, it can be shown that the majority of the tumuli are quite circular in plan view. This can be explained by the randomness in the direction of the principal forces during the crystallization of the gypsum. The reprecipitation of gypsum occurs at any point within the

gypsiferous layer, in the intracrystalline and intercrystalline voids, and on this basis the forces generated must be isotropic forces, with the ellipsoid of spherical deformation being that which provokes subcircular doming in order to compensate for the volumetric change.

The analysis of data concerning the flow velocity necessary to obtain gypsum saturation in the cap of the tumulus (Figure 4) leads one to believe that it is necessary, after rainfall or overnight condensation of dew, for a sudden evaporation. This would cause water to ascend (extraction by evaporation without dismissing capillary effects), impregnating the pores and fissures and maintaining the water–rock contact for longer. The process described can be accommodated by the generative hypothesis described earlier, in that the sudden ambient climatic changes, such as precipitation and intense evaporation of a cyclical nature, are fundamental for the formation of a tumulus.

Figure 5a depicts the general scheme considered in the present article. Highly aggressive infiltration water provokes the intercrystalline and intracrystalline dissolution of a gypsum crystal (Figure 5a, 1 and 2). Percolation is effective to the depth marked by lithological discontinuities such as fine pelitic laminae. Subsequent evaporation due to intense daytime insolation allows saturation of gypsum to be reached within the interstitial fluid (Figure 5a, 3). The secondary microcrystalline gypsum precipitated in the intercrystalline or intracrystalline spaces confers a higher porosity than the original macrocrystalline gypsum. This increase in porosity, together with the force of crystallization of the gypsum, leads to a relative increase in volume which is translated into gentle folding (Figure 5a, 4). The tumulus thus formed develops progressively, subjected to a continuous cycle of dissolution and reprecipitation of the gypsum within it, a cycle which constantly modifies the volume and porosity of the stratum until the doming compromises the stability of the tumulus itself.

Figure 5b, by means of a series of enlarged SEM microphotographs, shows the characteristics of microcrystalline gypsum present between the contacts of the gypsum macrocrystals. This phenomenon is corroborated at a macroscopic level by the presence within the tumulus fields of areas where gypsum is manifest as a structure with a karren mosaic of dissolved crystals, on the edges and exfoliation planes perpendicular to the land surface, and which are cemented within a gypsiferous neoformation matrix of whitish colour.

Finally, the fact that the genesis of tumuli is presented as a continuous cyclical process accords with the evidence that tumuli are formed chiefly in semiarid climates, where, after the scarce and sporadic rain or even the overnight condensation of water, there follows a period of sudden evaporation that provokes precipitation of gypsum leading to a progressive lifting of the domed cap of the tumulus. However, it is also possible to encounter tumuli in areas of greater precipitation, such as in the case of Bologna or Sicily, if the exaggerated evaporation conditions exist locally, as can occur on slopes exposed to intense seasonal insolation.

The process presented is novel in that it does not require the involvement of other, more complex processes such as hydration of anhydrite (non-existent in the gypsum outcrop of Sorbas, the example considered here) in order to justify the changes in volume implied in the doming of the gypsiferous layer.

CONCLUSIONS

The genesis of tumuli is related to processes of dissolution and precipitation in the raised gypsiferous dome. For this lifting process to take place it is not necessary to implicate either tectonic phenomena or anhydrite–gypsum transformations generating changes in volume.

The quasi-simultaneous dissolution and precipitation within a single gypsiferous layer is demonstrated by the textural changes detected between the original macrocrystalline gypsum (nanopits and microkarren related to exfoliation) and the reprecipitated microcrystalline gypsum (decrease in crystallinity and increase in secondary porosity).

Gypsum saturation can be achieved within the limited thickness of the domed layer of a tumulus provided that the flow is slow and/or given the existence of capillary phenomena caused by intense evaporation which act to invert the infiltration.

The reprecipitation of microcrystalline gypsum in the interstices, both intra- and intercrystalline, causes a change in the volume of the gypsum cap and its consequent lifting. The collapse of the vaulted layer of the

tumulus occurs once gravitational instability has been incurred: such instability occurs as a result of the disruption of the equilibrium between dissolution and precipitation and the consequent changes in porosity and cohesivity of the tumulus cap.

The development of tumuli is a cyclical progressive phenomenon, favoured by the alternation of extreme conditions of evaporation and dissolution which are characteristic of semiarid climates.

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